

# Double-Layered Control Methodology Combining Price Objective and Grid Constraints

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**Abstract**— A major challenge consists of considering all stakeholders of the future Smart Grid, each with their specific and possibly opposing objectives. A distribution network operator aims at guaranteeing power quality criteria while consumers aspire lowering their power consumption bill. This fundamental issue currently delays the transition from small-scale research projects to a large-scale all-encompassing smart distribution grid. This paper describes a double-layered control methodology using the available flexibility of the majority of discrete smart appliances currently in use. The effect of striving for the objectives separately as well as in combination is examined. The results show that the targeted objective(s) strongly influence(s) the performance in terms of cost effectiveness as well as number of voltage issues.

**Keywords**—LV distribution grid, local voltage control, coordinated control, DSM, real time pricing, smart grid

## I. INTRODUCTION

Over the last decade, there has been a clear focus in the European Union on promoting low-carbon generation technologies and renewables. By 2020, the European Union targets 20% of power generation from renewable sources. In many countries across Europe, this has already led to an increasing penetration of smaller-scale generation into distribution networks [1]. The Belgian action plan for renewable energy (NREAP) estimates an increase in the amount of renewable energy from 2.6 GW in 2011 to 11.4 GW in 2020 [2].

Simultaneously, the total energy consumption is rising steadily by several percent per year [3]. These rates of change will only rise in number as opportunities for electrification of transport (EV) and heat production (heat pump, electric boiler) arise since fossil fuels become more expensive and consumer energy awareness grows [4].

This evolution is leading to increasingly complex power flows, pressurizing the European low voltage (LV) distribution networks currently in use. Distribution system operators (DSOs) are facing more variable and less predictable power flows, as well as increased (local) peaks in production and consumption, influencing the (local) voltages which are subject to strict regulation. Their historical “fit-and-forget” design, at that time corresponding with the unidirectional

power flows from generator to the end user and their predictable load profiles, now becomes more challenging to maintain.

A transition towards actively managing, monitoring and controlling the distribution network over a reliable communication infrastructure could drastically enhance the distributed generation capacity and permit the steep increase in energy consumption. This intelligent grid or Smart Grid (SG) would be capable of maintaining the grid within the acceptable region according to the EU EN50160 standard [5] while minimizing or avoiding any capacity upgrades. Likewise, valuable flexibility of consumers can be embedded in the operational management of the network by balancing their demand with the intermittent distributed supply using communication-based Demand Side Management (DSM) algorithms.

Contrary to the transmission system operator (TSO), DSOs are confronted with a key duality regarding the communication architecture. Real-time coordinated control of demand and supply requires a reliable communication, while the vast number of communicating devices ineluctably necessitates a low-cost solution. Furthermore, a well-designed layer of intelligence requires tight integration of smart meters, household devices and distribution transformers [6], requiring an interoperable communication infrastructure, employing standardized protocols. A further challenge consists of considering all stakeholders of the future smart grid, each with their specific and opposing objectives. DSOs aim at guaranteeing power quality requirements they have to satisfy by regulation, energy suppliers strive for maximal predictability of production and consumption in their energy portfolio and consumers aspire lowering their power consumption bill.

Therefore, this paper discusses a robust double-layered control methodology for aspiring the objectives of multiple market actors. First, high-level coordinated control of the device’s power set points is used in normal conditions to optimize power flows when aspiring the Balancing Responsible Party (BRP) objective. This objective is incentivized through transmission of Real Time Pricing (RTP)

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signals, reflecting the cost of the BRP of generating and/or purchasing electricity at the wholesale level. Transmission of these signals to the households allows for more active involvement of the demand side. Secondly, a low-level voltage droop control is used as a backup mechanism in response to abnormal grid conditions and malicious or absent coordination. The main advantage of this split-design choice is that the lower droop level does not require a communication network between the different households, since only locally available measurements, such as the household supply voltage, are taken into account. Furthermore, this control mechanism is compatible with the smart devices being used in the Linear field test [7].

This paper is organized as follows. Section II explains how the developed control system works. Section III clarifies the simulation scenario, and section IV gives simulation results. The conclusion of the work and future work is discussed in Section V.

## II. DOUBLE-LAYERED CONTROL METHODOLOGY

As stipulated in [8], depending on the varying and often contradictory objectives of the different participants in the electricity markets three different SG concepts are distinguished. First, the Market Oriented SG concerns the energy market and does not affect network operation. This form of SG satisfies the needs of the BRPs, consumers and retailers. This requires a high-level coordinated control architecture for balancing demand and supply.

Secondly, the Grid Oriented SG entails the interests from the grid operator perspective. Their objective is to reduce investment and maintenance costs of the electric infrastructure. Infrastructure-wise, this corresponds to a robust low-level droop controller.

Finally, these concepts can be united in the System Oriented SG, optimizing the system as a whole, both from the standpoint of keeping the energy balance as well as from the perspective of grid operation and management.

As a result, we propose a control system being highly (high-level) as well as not (low-level) dependent on communication. Moreover, the lower control level can also be used as a fallback mechanism for the communication-based layer when communication fails or when the system has been compromised due to cyber security issues [9]. This system is also compatible with the DSM infrastructure currently being used in the Linear field test, as will be discussed in the simulation scenario (section III). Both control layers are now separately discussed.

### A. Low level layer: discrete voltage droop

The voltage droop control layer aims at satisfying the DSO's objective, and corresponds with the Grid Oriented SG vision. In the classic droop control, devices having an inverter-like front-end react instantaneously to voltage and/or frequency deviations by changing their power output linearly between a minimum and maximum value [10,11]. Here however, we

translate the classic droop control towards on/off switching of discrete devices, with an update frequency of fifteen minutes which is consistent with the control frequency of the majority of existing DSM algorithms [12].

In order to decide which devices to switch on or off, a hierarchical priority-based ordering scheme is used. The *priority* of a smart appliance is defined as a measure of the urgency to start. When a device almost needs to switch on to preserve the comfort settings of the user, its priority is high. When there still is some time left before it needs to switch on, its priority is low. The device priorities increase linearly to the time of departure or expiration of the flexibility deadline, and are calculated as:

- Electric vehicles and white good appliances:

$$priority(t) = 100 \frac{t - t_{setup}}{t_{setup} - t_{deadline}} \quad (1)$$

- Electric hot water boilers:

$$priority(t) = 100 \frac{SoC(t) - 100}{SoC_{min} - 100} \quad (2)$$

with  $t$ , the current time step,  $t_{setup}$ , the time at which the user programs or connects the device,  $t_{deadline}$ , the time at which the appliance has to complete its cycle,  $SoC$ , the state of charge of the boiler, and  $SoC_{min}$ , the minimal allowed state of charge of the boiler, as set by the user. For an electric vehicle,  $t_{deadline}$  equals the expected time of departure.

Based on the average voltage during the previous fifteen minutes, one or more devices are switched according to the hierarchical device ordering scheme, as can be seen in Fig. 1. It shows that when a certain under or over voltage limit is reached, the Lower and Upper Droop Limits (LDL, UDL) respectively, a load switches on or off. The respective smart appliances are graphically represented by the rectangles L1 to L4. The height of these rectangles represent the power rating of the load. When a voltage higher than the UDL is measured, the highest priority device is switched on first. When a voltage below the LDL is measured, the device with the lowest priority is switched off or delayed first. In the example given in Fig. 1, L1 has a higher priority than L2, whilst L3 has a lower priority than L4. For a full description of the operating principle refer to [13]. Table I shows the discrete droop parameters used in this paper.

TABLE I. DISCRETE DROOP PARAMETERS

Parameter	Value
Lower Droop Limit (LDL)	4% of $U_{nom}$
Upper Droop Limit(UDL)	4% of $U_{nom}$
$\alpha_{lower}$	$\tan^{-1} \left( \frac{\sum P_{devices}}{0.1 U_{nom} - LDL} \right)$
$\alpha_{upper}$	$\tan^{-1} \left( \frac{\sum P_{devices}}{0.1 U_{nom} - UDL} \right)$

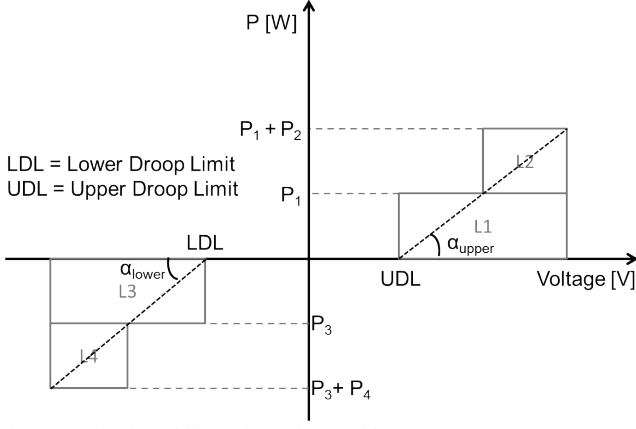


Fig. 1: Priority-based hierarchical droop table [13].

### B. High level layer: three-step approach

The high-level communication-dependent control layer consists of a three-step approach as presented in [14], and corresponds with the Market Oriented SG vision. The optimized scheduling of all smart devices is done every fifteen minutes, which is again in line with the wholesale energy market timeslots and the limitations of the field test hardware.

In the aggregation step, consumption constraints are aggregated in a hierarchical agent based structure with data aggregation on the different levels. At various hierarchical levels the algorithm takes into account aggregated flexibility boundaries, an area which is bounded by the energy constraint vectors  $\mathbf{E}_{max}$  and  $\mathbf{E}_{min}$  of the cluster of (smart) households under control. These values are the aggregated energy consumption values from the energy constraints of each smart device  $i$  when charging immediately or with maximal delay respectively:

$$E_t^i = 0 \quad t \in \{0\} \quad (3)$$

$$E_t^i = E_{req}^i \quad t \in \{t_{deadline}^i\} \quad (4)$$

$$E_{t+1}^i = E_t^i + P_t^i \Delta t \quad t \in \{0, \dots, t_{deadline}^i\} \quad (5)$$

$$E_{t+1}^i = E_t^i + P_t^i \Delta t \quad t \in \{0, \dots, t_{deadline}^i\} \quad (6)$$

$$P_t^i \in \{0, P_{max}^i\} \quad t \in \{0, \dots, t_{deadline}^i\} \quad (7)$$

$$\mathbf{E}_{max}^i = \{E_{t_{max}}^i | E_{t_{max}}^i = \min(P_{max}^i t, E_{req}^i), \forall t \in \{0, \dots, t_{deadline}^i\}\} \quad (9)$$

$$\mathbf{E}_{min}^i = \{E_{t_{min}}^i | E_{t_{min}}^i = \max(E_{req}^i - P_{max}^i(t_{deadline}^i - t), 0), \forall t \in \{0, \dots, t_{deadline}^i\}\} \quad (10)$$

$E_{req}^i$  is the required energy for a device to remain within its comfort settings. For an EV, this is the required energy to regain a maximal state-of-charge of the batteries. For the

white goods, it constitutes the required energy to finish the specific program. Finally, for the boiler this is the required energy to maintain the water at minimal state of charge given a certain hot water demand.  $E_t^i$  is the time-dependent energy the device consumes. For a boiler or EV this value can be discontinuously incremented, whilst for a white good the energy increases continuously. For a boiler or EV,  $P_t^i$  can be  $P_{max}^i$  or zero during the entire fixed time-slot of  $\Delta t$  being 15 minutes, whilst for a white good the power varies in amplitude depending on the execution moment in the sampled power train.

In the optimization step, Linear Programming is used to derive an optimal collective charging plan for the cluster of households. This cost minimization is based on hourly residential prices  $\mathbf{c}$ , reflecting the underlying cost of energy, for the upcoming day as derived in [15]. The optimization problem can be formulated as follows:

$$\min \sum_{t=1}^N x_t c_t \quad (11)$$

subject to:

$$\begin{aligned} 0 &\leq P_t \leq P_{max} \\ E_t^{min} &\leq E_t \leq E_t^{max} \\ E_{t+1} &= E_t + P_t \Delta t \end{aligned}$$

With  $\mathbf{x}$  the cluster energy consumption to be optimized for the specified time period within the flexibility area, which is bounded by the energy constraint vectors  $\mathbf{E}_{max}$  and  $\mathbf{E}_{min}$  of the cluster of controllable devices. These values are the aggregated energy consumption values from the energy constraints of each smart device  $i$  when charging immediately or with maximal delay respectively.

Finally, in the real-time control step, the optimal consumption schedule from (11) is used to create an incentive signal for all smart devices, by using a walrasian market mechanism with demand and supply functions. Fig. 2 shows an exemplary optimal device scheduling for one household and each of its smart appliances.

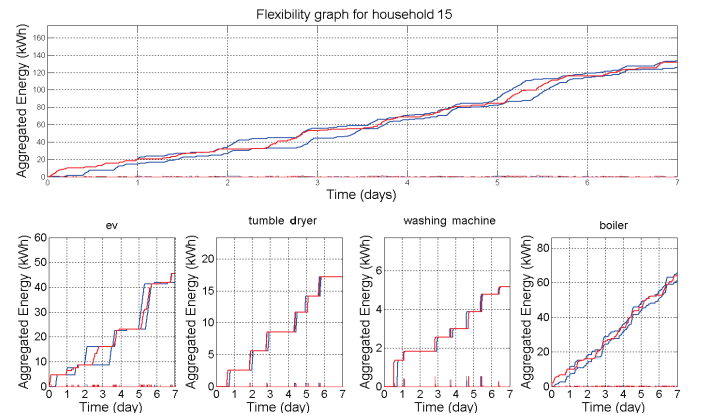


Fig. 2: Flexibility graph for household 15 (top) aggregated and (bottom) device specific for the EV, white goods appliances and boiler respectively. The optimized (cluster of) device(s) consumption, subject to their respective energy constraints vector in blue, is shown in red.

### III. SCENARIO

The individual elements of the control methodology will be implemented and tested in a real life pilot test from mid-2013 until mid-2014 [7]. The requirement to use readily available equipment has a number of consequences in terms of control system specifications and design choices that were made.

First, all smart appliances that will be managed by the control system are appliances that can only be switched on or off. No power modulating device behavior is possible. The smart appliances that will be used are white good appliances (i.e. dishwashers, washing machines and tumble dryers), electric hot water boilers, and electric vehicles.

#### A. Grid topology

The proposed control methodology is tested on an existing distribution feeder that will be used during the pilot test. The feeder (230/400V nominal voltage, 50Hz) is located in Flanders, Belgium, and has a TT grounding arrangement. The feeder has a three-phase topology, with both underground and overhead connections. The topology is shown in Fig. 3. The voltages on the feeder are calculated using a backward-forward sweep static load flow, taking into account the three-phase unbalance, and is implemented in MATLAB [16].

#### B. Smart households

Fig. 3 shows that 15 out of the 38 households are smart households, meaning they are equipped with one or more smart appliances. The total amount of controllable devices equals 13 washing machines, 10 tumble dryers, 9 dishwashers, 6 electric hot water boilers and 4 electric vehicles.

#### C. PV installations

Twelve households are equipped with a PV installation. The used PV profiles are derived from measurements on one existing installation at the KU Leuven. PV Installations larger than 5.9kWp are three-phase connected as imposed by regulations [17].

#### D. Household load profiles

Each simulation, a set of 38 load profiles is selected. The available load profiles are statistically representative for the population in Belgium, and were measured on a 15 min. basis. Only the active power was measured, so reactive power is neglected in the simulations. All smart appliance profiles (white good, EV, electric hot water boiler), as well as PV profiles are added up to these uncontrollable base load profiles where applicable.

#### E. Smart appliances: white goods

The power profiles of the dishwasher, washing machine and tumble dryer are based on synthetic models of the respective appliances [18]. In the simulations we assume that the users offer a normally distributed appliance flexibility with a mean of four hours and a standard deviation of one hour. In the pilot test, the smart white good appliances are unable to interrupt their running cycle once started.

#### F. Electric vehicles

A total of 4 single-phase connected electric vehicles are randomly distributed over the smart households. Their battery SoC, arrival and departure times are based on an availability study, based on Flemish mobility behavior, given in [19]. It is assumed that the EVs only charge at home and are plugged in each time they arrive there. The discrete charging power and battery capacity are identical to the specifications of the Renault Fluence [20], which is used in the pilot test. The charging of the electric vehicle can be interrupted at any discrete time step of fifteen minutes.

#### G. Electric hot water boiler

The electric hot water boiler is modeled according to [21]. The boiler parameters are those of a Siemens DF2017 as this is the boiler deployed in the pilot test. The boilers in the pilot test are able to switch fully on or off at any instant, provided that the State of Charge (SoC) does not fall below the minimal allowed SoC, or rises above a SoC of 100%.

### IV. SIMULATION RESULTS

In order to investigate the effectiveness of the control methodology in satisfying the different objectives, a total number of 16 simulation runs were carried out, each with a duration of 60 winter days. First, power quality gains for the DSO and cost savings for the consumer are compared by varying  $P^{max}$  from (11) in 7 steps for the Market and System Oriented SG scenarios. Next, the Grid Oriented SG scenario is simulated where only the DSO objective is of importance. The final simulation run encompasses the base-case behavior where all smart appliances are being used as dumb ones, entailing instantaneous device consumption. On average, the schedulable household consumption equates to 559 kWh for the simulation period.

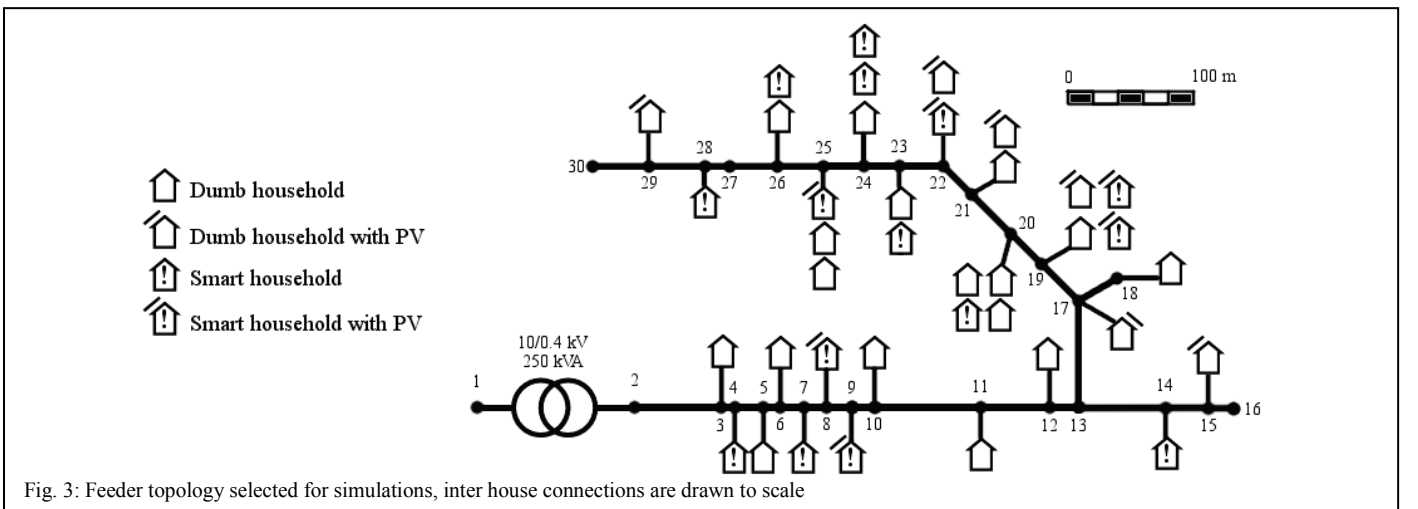


Fig. 3: Feeder topology selected for simulations, inter house connections are drawn to scale

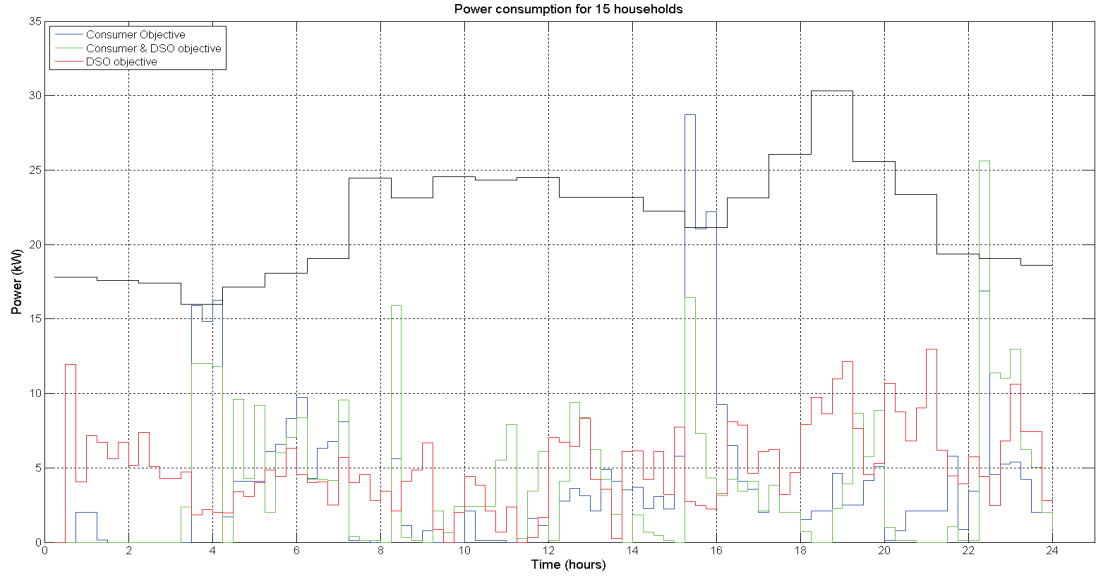


Fig.4: Aggregated power consumption for the cluster of 15 households when pursuing the consumer objective (blue), combined consumer and DSO objective (green) and DSO objective (red) during 24 hours. The RTP is shown in black.

The major differences between the three SG scenarios are depicted in Fig. 4, showing the resulting power consumption for the cluster of fifteen households during one day when aspiring the consumer, DSO, or combined consumer and DSO objectives. As immediately can be seen, the isolated consumer objective leads to large consumption peaks when the prices are low. When also accounting for the DSO objective however, these peaks in demand are no longer achievable due to interference of the low level droop controller. Besides switching off appliances when demand is high, devices are also being switched on during noon to account for over voltage issues when demand is low. Finally, only aiming for the DSO objective schedules the devices in such a way that maximal flexibility for compensating under voltages as well as over voltages is available. This leads to a smooth power consumption.

The trade-off between the harshness of optimization on cost and the number of voltage issues is shown in Fig. 5. The solid lines indicate the increasing cost savings for increasing values of  $P^{max}$  from equation (11). It can also be seen that savings are higher when only aspiring the consumer objective. The dashed lines show a marginally increasing number of voltage issues when relaxing the optimization power constraint, and a significant difference in number of voltage issues between both objectives. A voltage issue is defined as a RMS mean value falling beyond  $\pm 10\%$  of  $U_{nom}$ . Finally, a numerical comparison on the same criteria between the three SG concepts and the base-case behavior can be found in Table II.

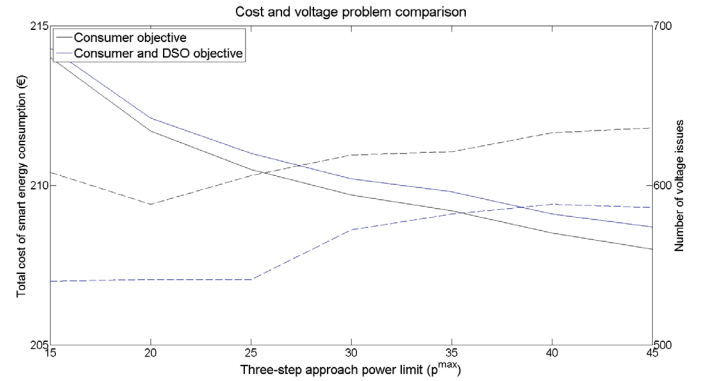


Fig.5: Comparison between average smart household consumption cost (solid) and total number of voltage issues (dashed) when using the three-step approach layer (consumer objective, black) and both control layers (consumer and DSO objective, blue) for all fifteen households.

TABLE II. COMPARISON BETWEEN SMART CONSUMPTION AND NUMBER OF VOLTAGE ISSUES, FOR VARIOUS VALUES OF  $P^{max}$

	Objective	Three-step approach power limit ( $P^{max}$ )						
		15	20	25	30	35	40	45
Cost <sup>a</sup>	Consumer	214.0	211.7	210.5	209.7	209.2	208.5	208.0
	Consumer/DSO	214.3	212.1	211.0	210.2	209.8	209.1	208.7
	DSO	225.7						
	Base-case	230.6						
Voltage issues <sup>b</sup>	Consumer	608	588	606	619	621	633	636
	Consumer/DSO	540	541	541	572	582	588	586
	DSO	593						
	Base-case	942						

<sup>a</sup>. Average cost of smart consumption per household during the simulation period of two months

<sup>b</sup>. Number of voltage issues for all households during the simulation period of two months

## V. CONCLUSIONS AND FUTURE WORK

A double-layered control mechanism using the available flexibility of smart devices within the Linear field test is developed. The main advantage of the developed control system is that it takes into account multiple objectives. The effect of the developed control system was tested with simulations on an existing LV distribution feeder, taking into account actual smart appliance presence.

Simulation results point out that the amount of over and under voltage occurrences on average decreased by approximately 8% when combining the droop objective with the consumer objective, while the price for the consumer only increased by 0.24% on average. Since the discrete droop only takes the locally measured voltage of the previous fifteen minutes into account for its control actions, and consumer comfort settings need to be satisfied at all times, future work entails a combination with a real-time power modular droop to completely satisfy the DSO objectives. Pro-actively accounting for the droop interaction in the higher control layer using a Reinforcement Learning technique [22] is also envisioned.

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